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Continental crust formation: Numerical modelling of chemical evolution and geological implications

U. Walzer*, R. Hendel

Institut f. Geowissenschaften, F.-Schiller-Universität, Jena 07743, Germany

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ABSTRACT

Oceanic plateaus develop by decompression melting of mantle plumes and have contributed to the growth of the continental crust throughout Earth's evolution. Occasional large-scale partial melting events of parts of the asthenosphere during the Archean produced large domains of precursor crustal material. The fractionation of arc-related crust during the Proterozoic and Phanerozoic contributed to the growth of continental crust. However, it remains unclear whether the continents or their precursors formed during episodic events or whether the gaps in zircon age records are a function of varying preservation potential. This study demonstrates that the formation of the continental crust was intrinsically tied to the thermoconvective evolution of the Earth's mantle. Our numerical solutions for the full set of physical balance equations of convection in a spherical shell mantle, combined with simplified equations of chemical continent–mantle differentiation, demonstrate that the actual rate of continental growth is not uniform through time. The kinetic energy of solid-state mantle creep (*Ekin*) slowly decreases with superposed episodic but not periodic maxima. In addition, laterally averaged surface heat flow (*qob*) behaves similarly but shows peaks that lag by 15–30 Ma compared with the *Ekin* peaks. Peak values of continental growth are delayed by 75–100 Ma relative to the *qob* maxima. The calculated present-day *qob* and total continental mass values agree well with observed values. Each episode of continental growth is separated from the next by an interval of quiescence that is not the result of variations in mantle creep velocity but instead reflects the fact that the peridotite solidus is not only a function of pressure but also of local water abundance. A period of differentiation results in a reduction in regional water concentrations, thereby increasing the temperature of the peridotite solidus and the regional viscosity of the mantle. By plausibly varying the parameters in our model, we were able to reproduce the intervals of the observed frequency peaks of zircon age determinations without essentially changing any of the other results. The results yield a calculated integrated continental growth curve that resembles the curves of GLAM, Begg et al. (2009), Belousova et al. (2010), and Dhuime et al. (2012), although our curve is less smooth and contains distinct variations that are not evident in these other curves.

1. Introduction

1.1. Integration of continental crust generation into a model of the thermochemical evolution of Earth

Early research suggested that Archean continental crustal material (e.g., tonalites and trondhjemites) was generated by the melting of mid-oceanic ridge basalt (MORB) slabs and Archean mantle wedges, with Proterozoic and Phanerozoic continental growth dominated by andesites and subduction-related rocks (Taylor and McLennan, 1995). Taylor and McLennan (1995) correctly recognised that the presence of abundant free water on Earth is one of the essential conditions for the generation of continental crustal material. However, recent basalt melting experiments indicate that modern MORB is not a plausible source for Archean continental crustal material that is dominated by tonalites, trondhjemites, and granodiorites (i.e., TTGs). The generation of TTGs requires a large ion lithophile element (LILE; i.e., K, Rb, Sr, Cs, Ba, and Eu^{2+} (Chauvel and Rudnick, 2016)) enriched source that is similar to the source of oceanic plateau basalts (Martin et al., 2014). The fact that water is not enriched at the base of present-day oceanic plateaus and that TTGs are produced by deep partial melting of hydrous basalt within the garnet stability field led Martin et al. (2014) to conclude that the occasional subduction of oceanic plateaus generated precursors to Archean continental crust. The present-day life expectancy of MORB crust is 150–200 Ma, whereas more buoyant oceanic plateaus are more likely to resist subduction. The upper layers of these plateaus are likely to peel off and be accreted to fertile continental margins or island arcs (Kerr, 2014).

* Corresponding author.
E-mail address: u.walzer@uni-jena.de (U. Walzer).

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The source region of an oceanic plateau must be hotter than the surrounding upper mantle (Kerr and Mahoney, 2007). The present-day mantle temperature beneath oceanic ridges is lower than the temperature of the mantle source of oceanic island basalts (OIB) (Herzberg et al., 2007; Lee et al., 2009). The modelling presented here indicates that elevated temperatures are the main driver of the partial melting of the source regions for oceanic plateau basalts. Lateral temperature gradients during the Phanerozoic have essentially been produced by large mantle plumes (McKenzie and Bickle, 1988) that arise as a consequence of the high temperature at the core–mantle boundary (CMB) (Davies, 2005). However, the volumetrically averaged Archean mantle temperature of our model is about 210 K higher than the present-day temperature of the mantle, a difference that is both consistent with komatiite research and suggests that some other process caused the elevated temperature of these mantle sources during the Archean, a process that was subsequently subdued during the Proterozoic and Phanerozoic.

van Kranendonk et al. (2011) and Brown (2014) used geological observations to suggest that one-sided subduction and steady-state plate tectonics initiated at about 3.0 Ga. This assumption is based mainly on the observation that prior to 3.0 Ga the subcontinental lithospheric mantle (SCLM) contained only peridotitic inclusions whereas later SCLM material preserved in diamonds contained eclogitic mineral inclusions. However, the modelling presented in this study does not impose any such restrictions, primarily as there are a number of different proposals for the timing of the onset of present-day type of subduction (cf. Fig. B11, where B refers to Appendix B). The possibility of a lack of modern-style oceanic crustal subduction in the Eoarchean and Mesoarchean also means that attempting to explain the early chemical evolution of the continental crust and the residual mantle by the differentiation of the oceanic crust is impossible, consistent with the geochemical reasoning of Martin et al. (2014). In addition, we know that 50%–70% of the continental crustal mass had formed by the beginning of the Neoarchean (Taylor and McLennan, 2009), with Belousova et al. (2010) concluding that more than 60% of the existing continental mass was generated before 2.5 Ga. This strongly suggests that the Eoarchean and Mesoarchean evolution of the Earth determined the initial conditions for the processes that operated during the Neoarchean, Proterozoic, and Phanerozoic, rather than the opposite. This in turn indicates that models of the geochemical evolution of the mantle that involve the early development of oceanic crustal subduction with later incorporation of chemical continental differentiation are erroneous. This conclusion is independent of the fact that continental differentiation must have involved two or more steps. Therefore, any modelling of the evolution of the continental crust and mantle must incorporate the notion that an essential part of the continental crust evolved prior to the onset of present-day steep subduction of the oceanic crust. In addition, crust–mantle differentiation is intrinsically tied to the thermal evolution of the mantle, indicating the importance of integrating a simplified model of continental–crust differentiation and accretion into a three-dimensional (3D) spherical-shell model of the chemical and thermal evolution of the Earth. This type of model contrasts with many other similar models in that it more closely accounts for the geological and mineralogical history of the Earth.

1.2. Are rates of continental crustal growth uniform through time?

The temporal distribution of zircon U–Pb ages throughout Earth history has peaks and troughs that can be explained by two end-member hypotheses, as follows.

(1) Zircon age peaks represent episodes of enhanced continental crustal generation with increased magmatism occurring prior to the collision of newly generated continental segments with older continents (Arndt and Davaille, 2013; Rino et al., 2004; Walzer and Hendel, 2013; Yin et al., 2012).

(2) Zircon age peaks are artefacts that reflect variations in preservation potential, as outlined by Hawkesworth et al. (2009), who stated that the time intervals preceding supercontinent formation have moderate preservation potential, whereas periods of supercontinent amalgamation have the highest preservation potential. This led Spencer et al. (2015) to emphasise that continental collision isolates collision-related tectonomagmatic belts from various tectonic processes, a process that increases the longevity of detrital zircon isotopic signatures. This type of magmatism is thought to be continuous and non-episodic. Zircon preservation potential is also thought to be low during supercontinent break-up, with Cawood et al. (2013) suggesting that continental growth occurred by a continuous rather than episodic process, consistent with research by Belousova et al. (2010) and Dhuime et al. (2012), who concluded that the rate of continental growth is relatively uniform through time.

Recent research supports hypothesis (1) and it is probably uncontested that the majority of continental growth during the Phanerozoic and presumably also the Proterozoic occurred in oceanic and continental arc settings. This view is supported by multi-element (Ba to Yb) variation diagrams (Niu et al., 2013) that show the similar compositions of bulk continental crust (Rudnick and Gao, 2003) and island-arc basalts (Elliott, 2003). In addition, water is necessary for the generation of granitoid magmas. One of the main regions for the generation of hydrous magmas at the base of the crust is island arc settings, where water is added to the mantle wedge from the down-going slab. In contrast, the base of present-day oceanic plateaus is anhydrous (Arndt, 2013). The largest Phanerozoic magmatic arcs were generated above subduction zones where 50% of the magmatism was derived from the mantle wedge, with the remaining 50% derived from recycled upper-plate crustal material (Ducea et al., 2015). In addition, Paterson and Ducea (2015) described episodic arc magmatism where flare-ups produce 100–1000 times more magmatic mass that is added to continental arcs compared with periodic lulls in magmatism. These Phanerozoic peaks in magma addition rates do not coincide with supercontinent formation but are consistent with peaks in the zircon age record (Ducea et al., 2015).

Given the above, the second main aim of our modelling is to determine whether continent generation is a continuous or episodic process. The modelling should be based on a physically sound and complete system of equations and should be able to predict other observable variables such as laterally averaged heat flow and the present-day volume of continental crust.

1.3. Origin of juvenile contributions to the continental crust

Present day plume-generated hotspots are anomalous volcanic regions that are not associated with contemporaneous plate boundaries (Davies et al., 2015). Current magmatism is the result of two different processes, namely plumes and plate tectonics, both of which are likely to have existed in the past. If modern plate tectonics with oceanic crustal subduction, arc formation, and accretion only initiated after 3.0 Ga then it is likely that continental crustal material that formed before this time evolved from oceanic plateau material. Early research suggested that the SCLM developed by the stacking of material derived from subducted oceanic slabs, although it is perhaps more likely that the Eoarchean and Mesoarchean SCLM and associated continental crustal material are the residues of very high-degree partial melting of the ambient upper mantle (a process that no longer occurs) or mantle plume material (Griffin et al., 2013). Similarly, Arndt et al. (2009) suggested that the main source